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Sizing and grid integration of residential PV battery systems

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Abstract

This paper analyses residential PV battery systems in order to gain insights into their sizing and grid integration. For this purpose a simulation model was developed and system simulations on a timescale of one minute were performed. Furthermore, a sensitivity analysis was conducted varying the PV system and battery size to identify appropriate system configurations. Based on the simulation results, an economic assessment of PV battery systems was carried out and the cost-optimal configurations for various cost scenarios were determined. Another focus of this paper is the integration of PV battery systems into the electricity grid. The impact of different operation strategies on the peaks and ramps of the feed-in power is analysed. The results show that forecast-based operation strategies are able to improve the grid integration of PV battery systems.

Keywords: PV battery systems; Self-consumption; Sizing; Economic analysis; Grid integration; Peak shaving; Feed-in limitation

1. Introduction

With the continuing deployment of PV systems in Germany, new PV-related challenges in grid operation are rising. By mid-2013, PV systems with a capacity of around 35 GWp were installed in Germany. This is sufficient to cover around 6% of the annual gross electricity demand with PV systems (Fig. 1a). On clear-sky days on summer weekends, up to half of the German load is temporarily covered by PV generated power at noon, as shown in Fig. 1b. Due to their availability, wind and solar energy will contribute major shares to a purely renewables based electricity supply in the future.

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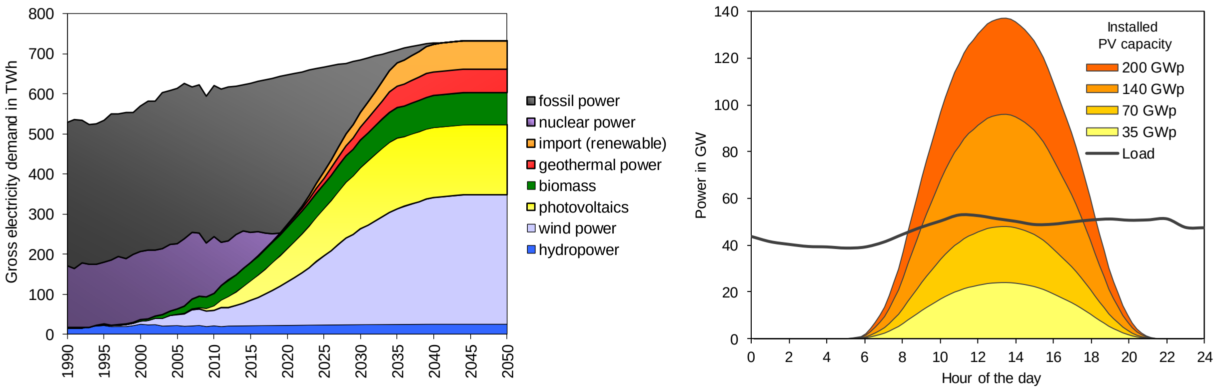

Fig. 1. (a) Previous development of the electricity generation in Germany and possible future development until 2050 for an electricity supply completely based on renewable energies [1]; (b) Impact of the PV generation on the electricity supply in Germany for different scenarios. Data (21/7/13): ENTSO-E (load), EEX (PV generation for the PV capacity of 35 GWp)

As presented in a long-term scenario in Fig. 1a, an annual average PV share on the electricity supply of more than 25% is a reasonable goal. This means that the PV generated electricity and the installed PV capacity have to increase at least by the factor of 5 in Germany. Nevertheless, if a PV capacity of 200 GWp is installed and the total generated PV power output is fed into the grid, temporary surplus situations of about 85 GW and ramps of the PV generation in the range of 30 GW/h will occur (Fig. 1b). This indicates an increasing need of appropriate compensatory measures in order to avoid a slowdown of the PV expansion for reasons of grid capacity constraints.

In the past, PV systems were mainly installed to feed the generated electricity into the electricity grid, which was remunerated with feed-in tariffs. However, in the beginning of 2012, the feed-in tariffs for PV systems below 10 kWp undercut the retail electricity prices for households in Germany [2]. With the increasing spread between PV feed-in tariffs and prices of grid electricity, using the PV generated electricity on-site on the household level is becoming more attractive than feeding it into the grid. Nevertheless, the simultaneity of the PV generation and load consumption in private households is limited. Shifting the consumption of deferrable loads by demand-side management to periods with PV surpluses is one solution to increase the local self-consumption of PV electricity in the residential sector [3]. The conjunction of PV systems with storage batteries allows a further increase of self-consumed PV electricity. With a battery system, the excess PV electricity during the day is buffered and later used at night. In this way, households equipped with a PV battery system can reduce the energy drawn from the grid and therefore increase their self-sufficiency. If a battery system is charged in the morning as soon as possible, the battery will be fully charged by midday on clear-sky days. Afterwards, the entire excess PV power is fed into the grid and feed-in peaks can occur. To limit the feed-in power and increase the self-consumption as well, forward-looking operation strategies of PV battery systems are required.

In this paper residential PV battery systems will be analysed by simulations in order to gain insights into their sizing and grid integration. In the next section the simulation model and the used input data are described. Afterwards, an energetic and economic assessment of residential PV battery systems is conducted to derive recommendations for cost-optimal sizing. Finally, the impact of different operation strategies on the PV feed-in will be investigated and appropriate control strategies will be identified to improve the grid integration of PV battery systems.

2. Approach

In order to analyse the energy flows of a household equipped with a PV battery system, a simulation model was developed. Both meteorological and load demand data sets were used as input for the simulation.

2.1. Input Data

To simulate the operation behaviour of PV systems, time series of meteorological data are required. For this investigation measurements from the metrological observatory Lindenberg, Germany, located at 52.21°N, 14.12°E in the south-east of Berlin, are used. The measured values are captured by the German weather service (DWD) in the framework of the Baseline Surface Radiation Network (BSRN). The global and diffuse irradiance on the horizontal plane as well as the air temperature are available as one minute average values from the year 2002 until 2006. The measured values of the year 2004 with a horizontal global irradiation of 1073 kWh/m² are used as a reference.

To depict typical fluctuations of the electricity consumption caused by switching of electrical loads in households, time series of the load with a high temporal resolution are needed. For that reason the guideline VDI 4655 (reference load profiles of single-family and multi-family houses for the use of CHP systems) is used as the data basis for load consumption [4]. For single-family houses the guideline includes measured data of typical daily load profiles from several households as one minute average values. To create an annual time series of the load, test reference years (TRY) of the DWD are necessary. With the TRY of the climate zone 4 (north-east German lowlands), a load profile for a single-family household was created for an entire year without considering holidays. The annual electricity demand of the household is determined to be 4 MWh.

2.2. Simulation Model

Residential PV battery systems can be distinguished in the connection of the battery between DC and AC coupled systems, as illustrated in Fig. 2. In AC coupled systems the battery is connected to the PV system, which consists of the PV generator and inverter, via a charge regulator and a battery inverter. In contrast, DC coupled batteries are connected to the DC link of the PV inverter. In this study, AC coupled residential PV battery systems are considered. The modelling of the system components is described in the following.

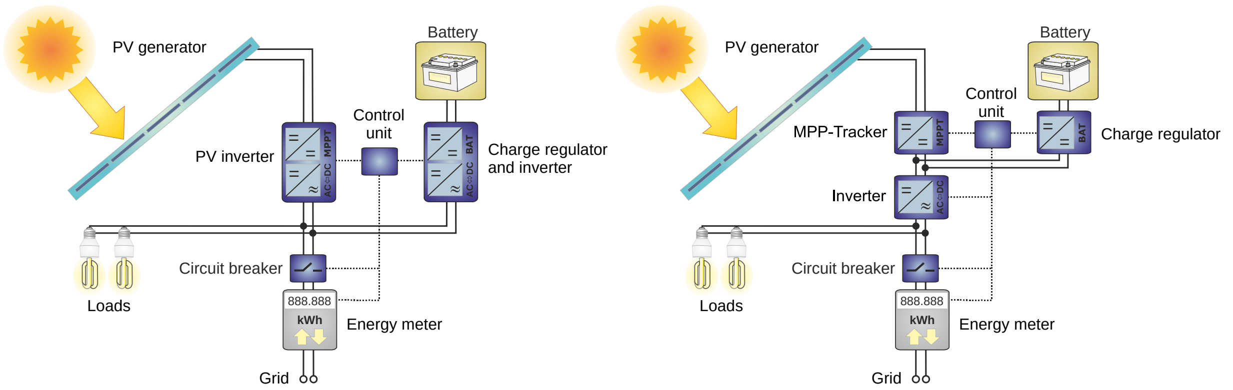

Fig. 2. System layout of AC coupled (a) and DC coupled (b) residential PV battery systems

It is assumed that the PV generator is south-oriented with a tilt angle of 35°. Therefore, the measured irradiance on the horizontal plane has to be converted to the plane of array. This is done geometrically for the direct irradiance and with the model suggested by Klucher for the diffuse irradiance [5]. Considering the reflectance of the environment with an albedo of 0.2, an annual sum of the irradiation on the PV generator of 1233 kWh/m² was determined.

To depict the impact of the irradiance on the efficiency of the PV generator, an efficiency curve of a multi-crystalline PV module was used. The increase of the PV generator temperature above the ambient temperature is assumed to be 29 °C for an irradiance of 1000 W/m², which is appropriate for rooftop systems with good ventilation. The thermal inertia of the PV generator was depicted with a PT1 element and a thermal time constant of 10 minutes [6]. The decrease of the PV power output due to increasing temperatures of the PV generator compared to the temperature of 25 °C is set to -0.4%/°C. Further PV generator losses of 8% are considered with empirical factors [7]. Additionally, average losses due to power degradation over 20 years are assumed to be 2%.

The dependence of the PV inverter conversion efficiency on the power output of the PV generator is considered with a parametric model [8]. The required model parameters are determined from data sheet specifications of a transformer-less inverter with a maximum conversion efficiency of 97%. The nominal power of the PV inverter is set to 1 kW/kWp. These models and assumptions result in an annual energy output of the PV system of 1024 kWh/kWp and a performance ratio of 83%.

In this study a lithium-based battery system is considered. The batteries are modelled with a simplified approach, considering a mean watt-hour efficiency of 95%. It should be noted that this neglects the dependence of the efficiency on several factors of influence like the discharging power, the temperature and the battery age. The state of charge of the battery is restricted to a range between 20% and 80% of the nominal battery capacity. Therefore, only a share of 60% of the installed battery capacity is usable. Hence, in this investigation all specifications of the battery size refer to the usable battery capacity.

Basically, the ageing of the battery leads to a decrease in battery capacity. The lifetime of a battery is defined as the period of time in which the capacity is reduced to 80% of the initial capacity [9]. Therefore, it is assumed that 90% of the usable battery capacity is indeed utilised within the lifetime on average.

The losses of the battery inverter are considered with a constant efficiency factor of 94%. This implies that the power dependent losses of the battery converter are not taken into account. The battery charge and discharge power normalised to the usable battery capacity is limited to 1 kW/kWh. The quotient of the energy output and the energy input on the AC side of the battery system is 84%.

Considering the simulation model described before, the system behaviour of a residential PV battery system is displayed for two example days in Fig. 3. The PV generation on a typical clear sky day is represented in Fig. 3a. The fluctuations of the PV power in Fig. 3b are caused by passing clouds. In general, the load with peaks during the day is influenced by the user behaviour and by the domestic appliances. The PV power output which can be consumed by the load at the same time is used directly on-site. In the case in which the PV power exceeds the load, surpluses occur. As long as the battery does not reach the maximum state of charge, the resulting excess PV power will be used for charging the battery, restricted by the battery inverter power. Otherwise, the surplus PV power will be fed into the grid. In the case in which the load exceeds the generated PV power, the battery is discharged until the minimum state of charge is reached. The remaining load is covered by energy drawn from the grid.

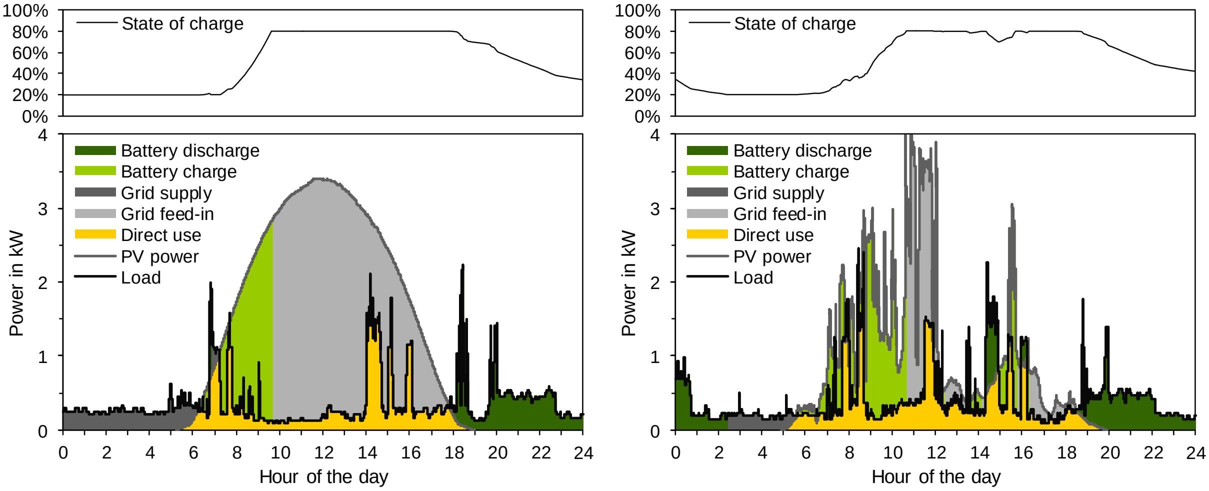

Fig. 3. Energy flows of a residential PV battery system on a clear sky day (a) and partly cloudy day (b) (PV system size 4 kWp, battery size 4 kWh, annual load demand 4 MWh)

3. Simulation of PV battery systems

On the basis of the simulation model and input data described above, simulations of PV battery systems with different system configurations are performed. To evaluate the simulation results, energetic assessment criteria have to be defined.

3.1. Energetic assessment criteria

One assessment criteria for PV battery systems is the realised self-consumption rate s, which is defined by the ratio between the PV energy which is used directly E_{DU} or used for charging the battery E_{BC} and the overall produced PV energy E_{PV}:

$$s = \frac{E_{DU} + E_{BC}}{E_{PV}} \tag{1}$$

The so-called degree of self-sufficiency describes the share of the load consumption that is supplied by the PV battery system. The degree of self-sufficiency d is calculated with the directly used PV energy E_{DU}, the energy discharged from the battery E_{BD} and the load demand E_L:

$$d = \frac{E_{DU} + E_{BD}}{E_L} \tag{2}$$

To evaluate the utilisation of a battery system, the number of storage cycles is a further benchmark [10]. The number of storage cycles n_c can be estimated by the ratio of the energy discharged on the DC-side of the battery system $E_{BD,DC}$ and the usable battery capacity E_{UB}:

$$n_c = \frac{E_{BD,DC}}{E_{UB}} \tag{3}$$

3.2. Sensitivity Analysis

The operation behaviour of PV battery systems and therefore the described energetic assessment criteria are influenced by several factors. To quantify those, a sensitivity analysis was performed. The impact of varying the PV system and battery size on the annual mean values of the self-consumption rate and the degree of self-sufficiency is shown in Fig. 4. Both the installed PV power as well as the battery capacity are normalised to the annual electricity demand of the household. This allows estimating the assessment criteria of single-family households with different annual electricity demands, neglecting the individual temporal distribution of the electrical loads in a household. As Fig. 4 shows, the self-consumption rate decreases and the degree of self-sufficiency rises with an increasing PV system size. But with larger sized PV systems the degree of self-sufficiency tends to saturate, since more PV surpluses occur that cannot be used simultaneously. Both assessment criteria are usually raised by an increasing battery size. With 1 kWp/MWh of PV system size a self-consumption rate as well as a degree of self-sufficiency of about 30% are achievable in single-family homes without a battery. For a household with an annual load demand of 4 MWh this PV system size corresponds to a rated PV power of 4 kWp.

If an additional usable battery capacity of 1 kWh/MWh is installed, the achievable self-consumption rate and degree of self-sufficiency will be increased to 59% and 56%, respectively. Another increase of the battery size of more than 1.5 kWh/MWh only leads to insignificant raises. This is due to the fact that large-sized battery systems are only partially discharged at night and not empty by the next morning. Therefore, the average load demand between sunset and sunrise is an appropriate benchmark for battery sizing in line with demand. Moreover, Fig. 4b reveals that 1 kWh/kWp of battery size is suitable to achieve high degrees of self-sufficiency. Also a usable battery capacity of more than 2 kWh/kWp should be avoided, since the fraction of the load demand delivered by the PV battery system cannot be increased any further. This is indicated by the vertical pathway of the isolines depicting the degree of self-sufficiency. Therefore, the battery size has to be chosen in relation to the nominal PV power as well as electricity demand of the household.

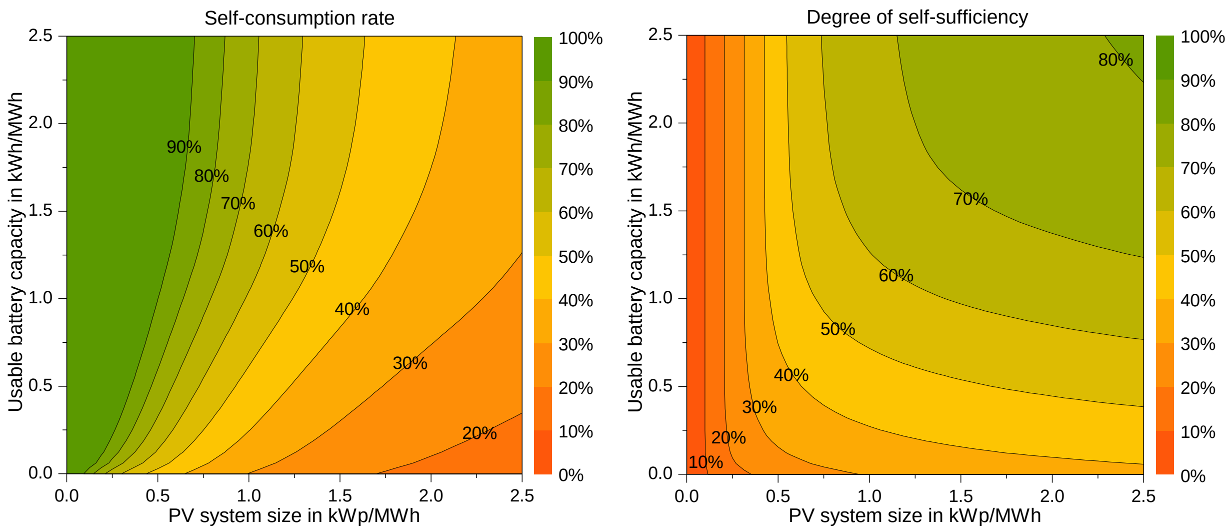

Fig. 4. Annual mean of the self-consumption rate (a) and degree of self-sufficiency (b) in dependence of the PV system and battery size, which are normalised to the annual electricity demand in MWh.

As mentioned above, the degree of self-sufficiency in Fig. 4b is determined for a south-oriented PV generator with a tilt angle of 35°. Since the orientation of the PV generator impacts the temporal distribution of the PV generation, it also affects the simultaneity of the PV generation and load demand and therefore the degree of self-sufficiency. In order to quantify this effect, the azimuth and tilt angle of the PV generator plane were varied. Fig. 5a represents the simulation results for a PV battery system with 1 kWp/MWh of rated PV power and 1 kWh/MWh of usable battery capacity. It can be seen that the highest degree of self-sufficiency is reached for south-oriented PV generators with an azimuth angle of 0°. For orientations that differ from the south, the self-sufficiency decreases. For an east-oriented PV generator with an azimuth angle of -90° and a tilt angle of 35°, a self-sufficiency of roughly 54% is achievable, which is only 2% lower compared to that of a south-oriented PV generator with the same tilt angle. Therefore, the orientation of the PV generator has no major impact on the degree of self-sufficiency for the considered load profile and PV battery system.

Besides the degree of self-sufficiency and the self-consumption rate, the number of storage cycles is a further benchmark. Also the annual number of storage cycles is strongly affected by the size of the PV battery system, as can be seen in Fig. 5b. In general, batteries in combination with small-sized PV systems only have few cycles and reach less than 150 cycles per year. This is because with small-scale PV systems only a few PV surpluses occur, which can be used to charge the battery. With an increasing PV system size the surplus PV energy rises and therefore also the number of cycles. A PV battery system with 1 kWp/MWh of PV power and 1 kWh/MWh of usable battery capacity reaches about 270 cycles a year. The highest annual number of storage cycles occurs in system configurations with a small battery capacity. Therefore the time period until reaching the maximum number of storage cycles is lower for small-scale battery systems than for larger sized systems. This indicates that the cycle lifetime of the battery is also highly affected by the system configuration.

It must be emphasized that all results presented above are influenced by the system technology, the used simulation models and input data as well as constraints. Especially the temporal distribution of the load demand and the PV generation has an impact on the energetic assessment criteria. The load profiles vary not only with the type of household but also with the domestic appliances the household is equipped with. Nevertheless, the presented simulation results can give an indication to estimate the energetic assessment criteria for PV battery systems in single-family houses in Germany.

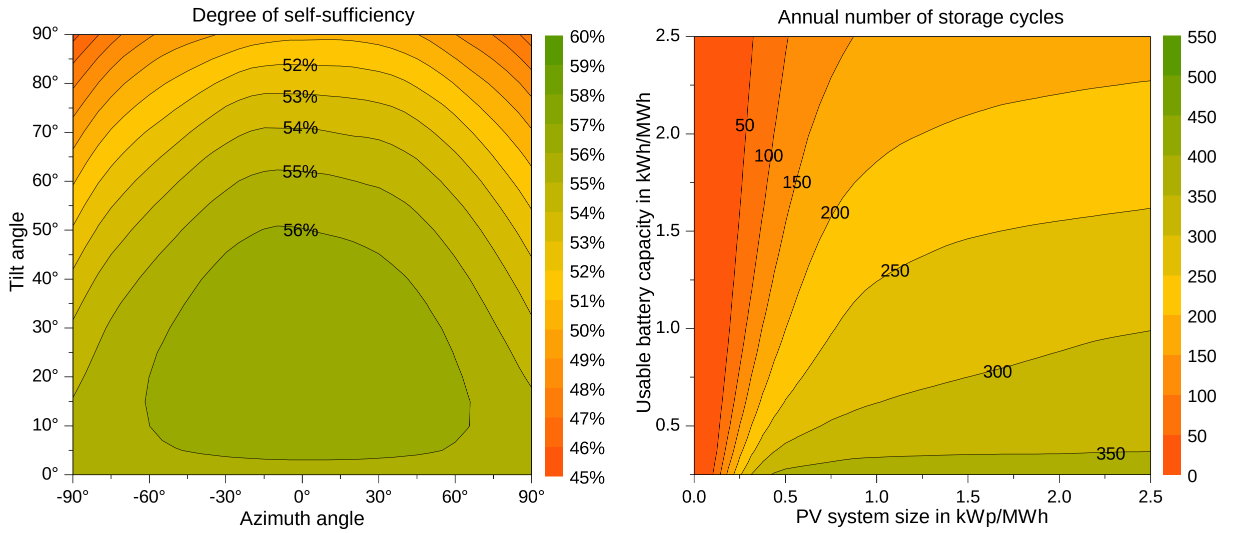

Fig. 5. (a) Annual mean of the degree of self-sufficiency in dependence of the orientation of the PV generator (PV system size 1 kWp/MWh, battery size 1 kWh/MWh); (b) Number of storage cycles per year in dependence of the rated PV power and usable battery size, which are normalised to the annual electricity demand in MWh.

4. Sizing of PV battery systems

After the energetic assessment of PV battery systems, different configurations are evaluated from the economic perspective. To identify the cost-optimal ratio of PV system and battery size, assessment criteria have to be defined.

4.1. Economic assessment criteria

The economic evaluation is performed using the annuity method. The annuity describes the annual payments of an investment including interest charges and repayments for an amortisation of the investment within a defined time period. The annuity factor a is defined by the interest rate r and the investment duration n as:

$$a = \frac{r}{1 - (1+r)^{-n}} \tag{4}$$

For a PV system the investment duration coincides with the operation lifetime n_{PV} of the system. The annual costs C_{PV} of the PV system are given by

$$C_{\mathrm{PV}} = I_{\mathrm{PV}} \cdot P_{\mathrm{PV}} \cdot (a_{\mathrm{PV}} + o_{\mathrm{PV}}) \tag{5}$$

using the annuity factor a_{PV} of the PV investment, the annual operation and maintenance costs o_{PV} normalised to the investment cost, the specific PV investment cost I_{PV} and the PV system size P_{PV}. Similarly, the annual costs C_{B} of the battery system are calculated as

$$C_{\mathrm{B}} = I_{\mathrm{B}} \cdot E_{\mathrm{BU}} \cdot (a_{\mathrm{B}} + o_{\mathrm{B}}) \tag{6}$$

using the annuity factor a_{B} of the battery investment, the annual operation and maintenance costs o_{B} normalised to the investment cost, the specific battery investment cost I_{B} and the usable battery capacity E_{BU}. To calculate the annuity factor a_{B} of the battery investment regarding equation (4), the achievable useful life of the battery system is required. The operation life n_{B} of the battery is restricted either by reaching the cycle lifetime t_{c} or by the calendar lifetime t_{a} [10]:

$$n_B = \min(t_c, t_a) \tag{7}$$

The cycle lifetime t_c can be estimated by dividing the maximum number of storage cycles n_{max} by the annual number of storage cycles n_c:

$$t_c = \frac{n_{max}}{n_c} \tag{8}$$

The average annual costs C_{GP} for the procurement of electricity from the grid are calculated with the average retail electricity price p_{GP}, the annual load demand E_L and the degree of self-sufficiency d:

$$C_{GP} = p_{GP} \cdot E_L \cdot (1 - d) \tag{9}$$

Besides the annual costs for the PV battery system and procurement of electricity from the grid, incomes from the remuneration of the grid injection of the PV generated electricity have to be considered as well. The annual revenues R_{PV} from the PV feed-in are calculated using the feed-in tariff p_{PV}, the average annual PV yield E_{PV} and the self-consumption rate s:

$$R_{PV} = p_{PV} \cdot E_{PV} \cdot (1 - s) \tag{10}$$

Considering all costs and revenues associated with the electricity consumption and production of the household allows comparing the profitability of different system configurations. Therefore, the mean price of electricity of the household during the operation lifetime of the PV battery system is a comparable measure to determine the cost-optimal configuration. The mean electricity price p_{EL} is obtained by dividing the sum of all annual expenses C_{PV}, C_B and C_{GP} as well as revenues R_{PV} by the annual load consumption E_L as follows:

$$p_{EL} = \frac{C_{PV} + C_B + C_{GP} - R_{PV}}{E_L} \tag{11}$$

The mean price of electricity varies with the PV system and battery size as well as all cost assumptions. The PV battery system size with the lowest mean electricity price corresponds the cost-optimal system configuration.

4.2. Assumptions

To identify the most economical configuration of PV battery systems, several assumptions have to be made. The calculation of the profitability is performed using an interest rate of 4%. For the PV system an operation lifetime of 20 years is assumed. The useful life of the battery is limited by 5000 cycles or by the calendar lifetime of 20 years. The annual operation and maintenance costs of the PV and battery system are set to 1.5% of the respective investment costs. It is assumed that the costs of the battery and the PV system are proportional to their size. Therefore the dependence of the specific investment costs on the size of the PV battery system is neglected. The mean retail electricity prices for households including value added tax (VAT) over the next 20 years are estimated to be 0.34 €/kWh in Germany. This value results from the current retail electricity price of 0.28 €/kWh and an annual increase of 2% over the next 20 years. Therefore the assumption of the average retail electricity price directly influences the economic assessment. As the profitability of PV battery systems is strongly affected by the cost situation, the following sensitivity analysis tries to reveal the impact of the possible future cost development on the economics of PV battery systems. The assumed payments for the grid feed-in and the assumed costs of PV battery systems for the different scenarios, which will be described in the following, are summarised in Table 1.

Table 1. Scenario of the possible future development of residential PV battery system costs and feed-in tariffs in Germany [11]

	Today	Short-term	Medium-term	Long-term
PV system costs (incl. VAT) in €/kWp	1800	1500	1200	1000
Battery system costs (incl. VAT) in €/kWh	3000	1500	1000	600
Feed-in tariff in €/kWh	0.15	0.11	0.06	0.02

4.3. Sensitivity Analysis

To determine the impact of the upcoming cost development on the cost-efficient size of PV battery systems, a sensitivity analysis is conducted for different scenarios according to Table 1. At present, typical specific costs for residential PV systems are about 1800 €/kWp and the grid injection is reimbursed with 0.15 €/kWh. The specific costs of lithium-based battery systems normalised to the usable battery capacity are in the range of 3000 €/kWh. Considering the current cost situation, Fig. 6a depicts the dependence of the mean price of electricity on the size of the PV battery system. The nominal PV power and the usable battery capacity are normalised to the annual load demand. If the household is not equipped with a PV battery system, the mean electricity price will be equal to the average retail electricity price, estimated to be 0.34 €/kWh. The investment in PV battery systems is economically favourable as soon as the mean electricity price of the system configuration falls below the average price for purchase of electricity from the grid. Therefore the limit of profitability coincides with the average retail electricity price. By installing a PV system without a battery, the mean price of electricity can be reduced today. Taking the current cost situation into account, the optimal PV system size with the lowest electricity costs is in the range of 2.2 kWp/MWh, indicated by the black dot in Fig. 6a. If the PV system is equipped with batteries at present, the mean electricity price will strongly increase. Coupling PV systems and large-scale battery systems leads to an average electricity price of 0.50 €/kWh or even more. Hence, from a purely economic viewpoint the conjunction of PV systems with large-sized batteries is not profitable yet under consideration of the described cost assumptions.

For the future it can be expected that the degression of the feed-in tariffs will be higher than the PV system cost reductions. As a consequence, the optimum will shrink to smaller-sized PV systems with higher self-consumption rates. Therefore, in the short-term scenario the PV system size with the lowest mean electricity price will drop to 1 kWp/MWh (Fig. 6b), assuming that the PV system costs and feed-in payments decrease to 1500 €/kWp and 0.11 €/kWh, respectively. If the battery system costs drop to 1500 €/kWh in the short-term, it will become profitable to install small-scale batteries with a usable battery capacity of up to 0.5 kWh/MWh. This reveals that PV systems combined with small-sized batteries will provide an economic benefit in the foreseeable future.

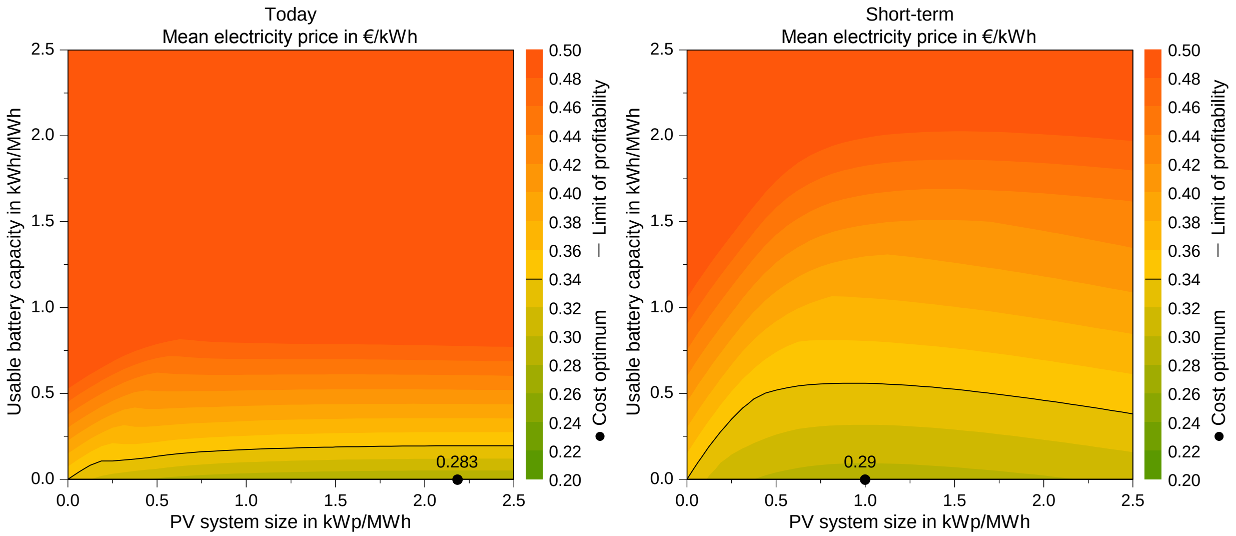

Fig. 6. Mean electricity price at present (a) and in the short-term scenario (b) in dependence of the PV system and battery size.

In the medium-term scenario costs for PV systems of 1200 €/kWp and feed-in tariffs of 0.06 €/kWh are assumed. With the increasing spread between the feed-in payments and PV generation costs, the optimal PV system size will decrease further. Taking the cost assumptions of the medium-term scenario into account, 0.6 kWp/MWh is the most economical PV system size (Fig. 7a). If battery system costs of 1000 €/kWh can be achieved in the mid-term, the conjunction of PV systems with medium-sized batteries will become economically feasible. Combining a rated PV power of 1 kWp/MWh with a battery size of 0.75 kWh/MWh results in an increase of the mean electricity price by 0.02 €/kWh compared to that of the optimal system configuration. Therefore, the mean electricity price will be increased only slightly if the configuration differs from the cost optimum.

In the long-term scenario costs are estimated to be 1000 €/kWp and 600 €/kWh for PV and battery systems, respectively. The remuneration of the PV injection is assumed to decrease to 0.02 €/kWh in the long-term. Based on these assumptions, combining PV systems with batteries will become the solution with the lowest costs in the long-term scenario. This means that installing a PV battery system is more attractive than installing a PV system without batteries. Fig. 7b reveals that the system configuration with a PV system size of 0.8 kWp/MWh and a usable battery capacity of 1.1 kWh/MWh is the most cost-efficient solution. However, a broad range of system configurations will be profitable. Nevertheless, PV system sizes above 1.6 kWp/MWh cannot compete against the grid electricity costs without a battery, due to their low self-consumption rates. It should also be highlighted that configurations enabling degrees of self-sufficiency above 70% are economically feasible in the long term (see Fig. 4b). In spite of the higher mean electricity price compared to the cost optimum, it can be reasonable to install such system configurations to reduce the reliance on possible future raises of grid electricity costs.

Fig. 8a reveals the refinancing of the determined cost-optimal configurations for the described scenarios. Whereas incomes from the feed-in have a strong contribution to the refinancing today, in the future their significance will decrease. With declining feed-in tariffs the savings of grid electricity costs contribute the major part to the revenues. This can be considered as a paradigm shift of the refinancing of the cost-optimal systems.

The results also reveal that the profitability of a PV battery system strongly depends on the price situation and assumptions. Therefore, Fig. 8b highlights the impact of the PV battery system costs on the mean electricity price of a typical system configuration in the long-term. It is evident that the costs of both components affect the profitability. Considering the PV battery system costs of 1000 €/kWp and 600 €/kWh assumed in the long-term scenario, this system configuration is profitable, since the mean electricity price is below the limit of profitability. An economical benefit can also be achieved with PV system costs below 1200 €/kWp and battery system costs below 1000 €/kWh. Hence, there is a broad scope of possible cost reductions for PV battery systems which are required to reach profitability. In conclusion, it should be pointed out that the profitability and the cost-optimal configuration can only be estimated, as the development of the electricity prices and household´s load demand in the future cannot be predicted precisely.

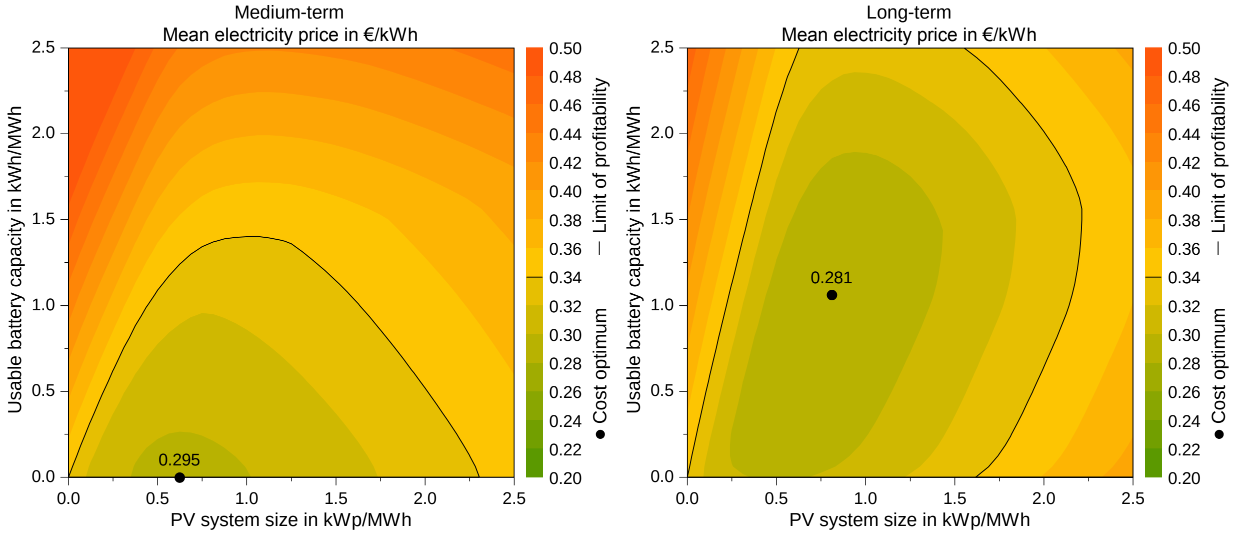

Fig. 7. Mean electricity price in the medium-term (a) and long-term scenario (b) in dependence of the PV system and battery size.

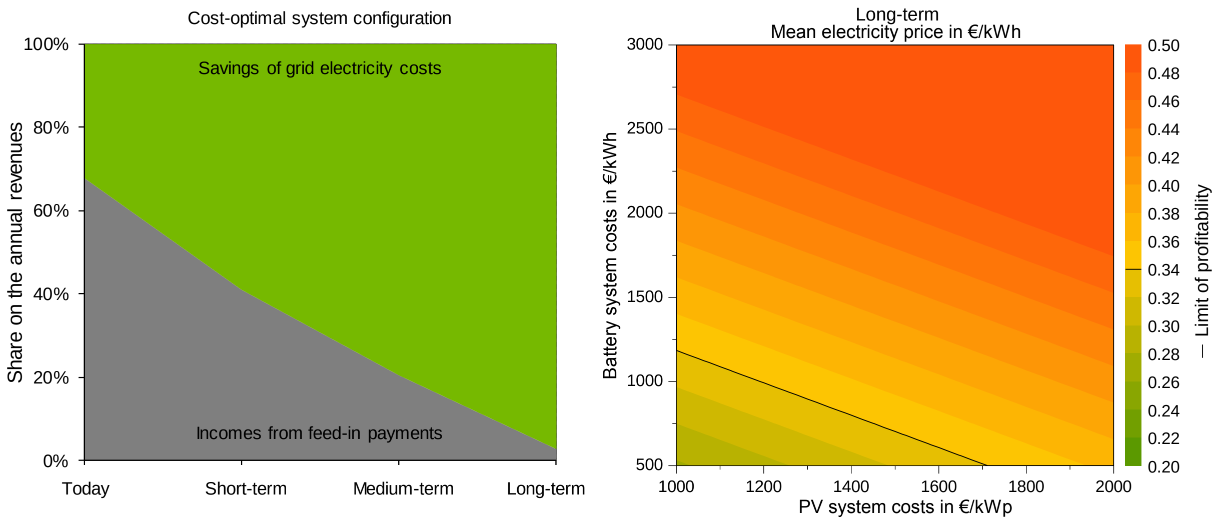

Fig. 8. (a) Contributions to the refinancing of the cost-optimal system configurations for the different scenarios; (b) Mean electricity price in the long-term scenario for varying PV and battery system costs (PV system size 1 kWp/MWh, battery size 1 kWh/MWh, feed-in tariff 0.02 €/kWh)

5. Grid integration of PV battery systems

The previous sections only consider the optimisation of PV battery systems on the household level. In the following, the integration of those systems into the electricity system is discussed and different operation strategies are evaluated.

5.1. Operation strategies of PV battery systems

Residential PV battery systems can be operated realising different objectives. Fig. 9 depicts schematically different control algorithms and their properties. The most common mode of operation aims to increase the self-consumption on-site, as described above. This is realised by charging the battery with surplus PV power as soon as possible. In consequence, the battery is usually fully charged by noon on clear-sky days. Afterwards, the entire excess PV power is fed into the grid (Fig. 9). Therefore, with this operation strategy feed-in peaks can occur and the loading of the grid cannot be reduced. To achieve this goal, the feed-in power can be restricted to a fixed level by charging the battery only with energy that exceeds this limit. By setting the feed-in limit to a fixed value which is too high, the amount of energy above this limit is not sufficient to charge the battery completely on cloudy days. As a result, the battery is utilised less and the self-consumption rate decreases.

To realise both the objective of maximising self-consumption as well as reducing feed-in peaks, forecast-based operation strategies are needed. By using household-specific load forecasts and site-specific PV generation forecasts for the day-ahead, the limit of the feed-in power can be adjusted with an iterative calculation approach every day. By setting the feed-in limit over the course of the day considering intra-day PV power output forecasts (Fig. 9), the grid injection of existing PV systems in the distribution grid can additionally be balanced by PV battery systems.

To reveal the potential of forecast-based operation strategies, the following simulation results are based on perfect forecasts of the PV generation and load demand neglecting deviations between the forecasted and actual values. Real load forecasts are derived from historical load data of the household and site-specific PV generation forecasts are offered by several commercial providers. Both are associated with forecast errors. It has to be mentioned that the impact of forecast errors on the system control behaviour is not taken into account, as perfect forecasts are considered in the following. However, with a dynamic approach over the course of the day, the occurrence of forecast errors can be balanced, too.

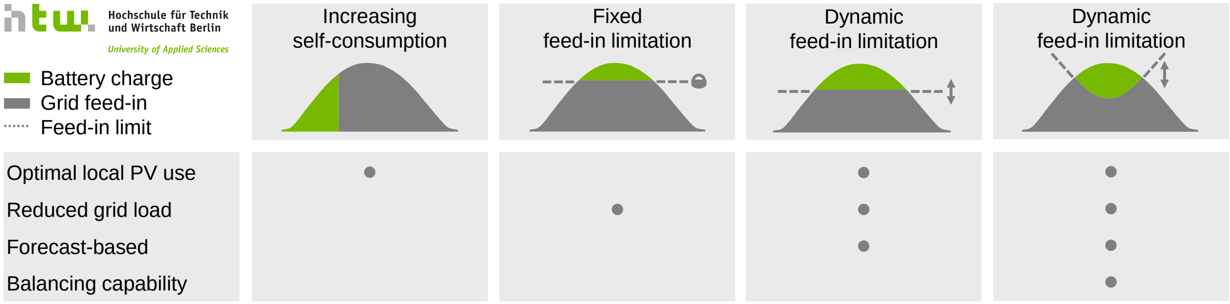

Fig. 9. Schematic representation of different operation strategies of PV battery systems and their properties

5.2. Power-related and energetic assessment criteria

The feed-in power characteristics of the described operation strategies can be evaluated by different assessment criteria. The feed-in power p_{GF} normalised to the rated power P_{STC} of the PV generator under standard test conditions (STC) is defined as

$$p_{GF} = \frac{P_{PV} - P_{DU} - P_{BC}}{P_{STC}} \tag{12}$$

were P_{PV} is the PV power output, P_{DU} the power directly used by the load and P_{BC} the power used to charge the battery. Analysing time series of the feed-in power, peaks of the grid injection can be identified. Furthermore, the intermittency of the feed-in power can be characterised by ramp rates [12]. The ramp rate r_{GF} of the feed-in power describes the change of the feed-in power p_{GF} between two time steps with an interval Δt:

$$r_{GF} = \frac{p_{GF}(t) - p_{GF}(t - \Delta t)}{\Delta t} \tag{13}$$

If the feed-in power is restricted to a certain limit, curtailing PV power may be required to observe the defined value. In consequence, energy losses due to curtailment will occur. The curtailment losses l can be determined with the total generated PV energy E_{PV}, the directly used energy E_{DU}, the energy used to charge the battery E_{BC} and the energy fed into the grid E_{GF} as follows:

$$l = \frac{E_{PV} - E_{DU} - E_{BC} - E_{GF}}{E_{PV}} \tag{14}$$

5.3. Sensitivity analysis

In the following, the different operation modes are investigated with regard to the occurrence of peaks as well as ramps of the feed-in power. First, the usable battery capacity that is required to limit the feed-in power to a certain level should be determined. For this purpose the energy losses caused by curtailing PV power are an appropriate benchmark. The curtailment of PV power will be required to observe the defined feed-in limit if the battery is fully charged before the excess PV power undercuts the feed-in limit. Fig. 10b displays the impact of the feed-in limit and battery size on the annual curtailment losses. Both the maximum feed-in power as well as the usable battery capacity are normalised to the rated PV power. In order to quantify the losses due to curtailment independently from the load demand, the simulation results are obtained neglecting simultaneous direct use of the PV power by the load of the household. Furthermore, it is assumed that the battery is completely discharged at night. In general, a decrease of the maximum feed-in power results in an increase of the energy amount above this feed-in limit and therefore in higher curtailment losses, as can be seen in Fig. 10a. To keep the feed-in power below 0.6 kW/kWp, losses due to curtailment in the range of 7% of the annual PV energy output occur. This value will increase to 34% if the feed-in power of a PV system is restricted to 0.3 kW/kWp.

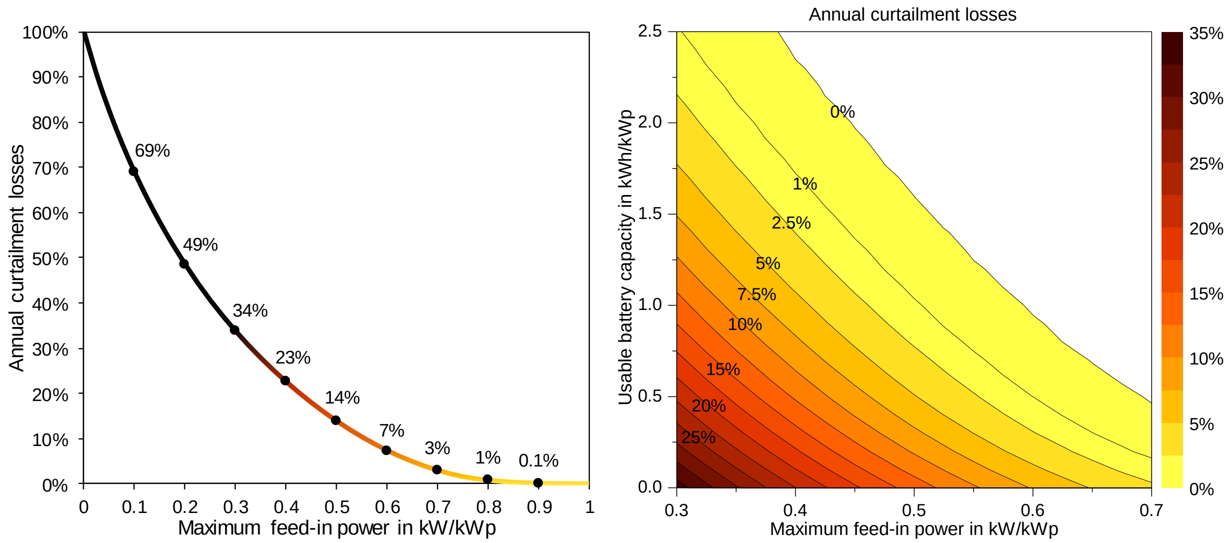

Fig. 10. (a) Impact of the feed-in limit on the annual curtailment losses related to the overall generated PV energy for a residential PV system without a battery system (neglecting self-consumption); (b) Annual curtailment losses in dependence of the feed-in limit and battery size (neglecting self-consumption, complete discharge of the battery system at night)

If a PV system with 0.6 kW/kWp of maximum feed-in power is equipped with 0.5 kWh/kWp of usable battery capacity, the curtailed energy can be reduced from 7% to 1% (Fig. 10b). To avoid the curtailment of PV power completely, the usable battery capacity has to be doubled to 1 kWh/kWp. This means there is not one day of the year in which the surplus PV energy above the limit of 0.6 kW/kWp is sufficient to charge the battery completely. Reducing the feed-in limit of a PV system from 0.6 kW/kWp to 0.4 kW/kWp will raise the curtailment losses to 23%. The losses will be reduced to 6% if this PV system is combined with 1 kWh/kWp of usable battery capacity. These results emphasize the required compromise between the maximum feed-in power, the installed battery size and the curtailment losses to realise appropriate feed-in peak shaving. However, the losses due to curtailment can be further diminished by consuming the PV power by the load of the household at the same time. By demand side management, the excess PV power and thereby the curtailment losses can also be reduced. Another option for reducing the curtailment losses consists in shifting the orientation of the PV generator to the east or west [13].

The impact of the described operation strategies on the feed-in power flows is reflected by sorted annual duration curves of the feed-in power, displayed in Fig. 11a. A typical PV system generates power about 4000 hours per year. The maximum feed-in power is restricted by the rated PV inverter power, set to 1 kW/kWp (see section 2.2). After considering the direct use of the PV power by the loads of a household equipped with a PV system size of 1 kWp/MWh, the feed-in power will be diminished (Fig. 11a). Combining this PV system with 1 kWh/MWh of usable battery capacity to increase the self-consumption, the duration of low feed-in power levels is strongly reduced. Nevertheless, the maximum power flows of the grid injection do not decrease significantly with the operation strategy of maximising self-consumption. This can be achieved by reducing the feed-in power to a fixed level of 0.6 kW/kWp. This is the lowest feed-in limit for this system configuration without allowing any curtailment of PV power. Since the battery is only charged with energy exceeding the limit of 0.6 kW/kWp, the duration curve of the feed-in power coincides with that of a PV system with self-consumption for power levels below this limit.

A significant reduction of the feed-in power is enabled by limiting the feed-in power dynamically on the basis of forecasts of the PV generation and load demand. By implementing this forecast-based approach into the described system configuration, the maximum feed-in power can be set to 0.4 kW/kWp, accepting curtailment losses between 1 to 2% of the annual PV generated energy. Compared to the operation mode of increasing the self-consumption rate, the dynamic feed-in power limitation approach also leads to an increase in the duration of the feed-in at low power levels.

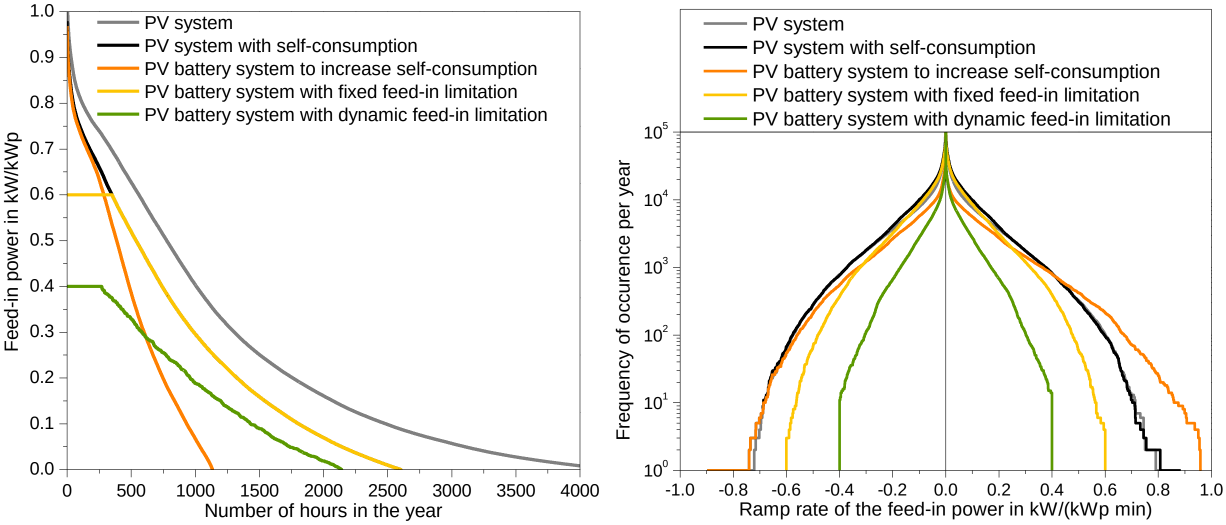

Fig. 11. Impact of different operation strategies of PV battery systems on the sorted annual feed-in power duration curve (a) and the frequency of occurrence of the feed-in power ramp rates (PV system size 1 kWp/MWh, battery size 1 kWh/MWh)

Apart from the peaks of the grid injection, also the ramp rates of the feed-in power are affected by the operation strategy of the PV battery system. Fig. 11b represents the frequency of occurrence of the feed-in power ramp rates for the different modes of operation. In general, positive ramp rates indicate an increase and negative ramp rates point out a decrease in the PV feed-in power between two time steps. In this investigation an interval between two time steps of 1 minute is considered. The maximum ramp rate of the feed-in power of a PV system observed in the simulation results are about 0.8 kW/(kWp min), caused by irradiance fluctuations through passing clouds. Most of the positive ramp rates are below 0.2 kW/(kWp min) and negative ramp rates are above -0.2 kW/(kWp min). Considering the direct use of the produced PV power only leads to small changes in the ramp rates. In the case in which the PV system is combined with batteries to increase the self-consumption rate, low levels of the negative ramp rates are slightly reduced. However, with this operation strategy higher positive feed-in ramps appear compared to those of a PV system without self-consumption. This is due to the fact that the feed-in power can increase rapidly after reaching the maximum state of charge of the battery (see Fig. 3).

When the feed-in power is restricted to a fixed value of 0.6 kW/kWp, it is obvious that the feed-in power ramp rates remain within ±0.6 kW/(kWp min). Therefore with a fixed feed-in limitation the high level ramp rates are reduced. Nevertheless, the highest reduction of the ramp rates is realised with the dynamic feed-in limitation with forecast-based operation modes. Since the feed-in power is limited to 0.4 kW/kWp, ramp rates between -0.4 and 0.4 kW/(kWp min) can occur. It can be concluded that forecast-based operation strategies of PV battery systems not only reduce the feed-in peaks but also smooth the intermittency of the PV feed-in power. Since the simulation results are obtained from perfect forecasts, possible negative impacts of forecast errors on the control behaviour are neglected. As mentioned above, forecast error related drawbacks can be mitigated by adopting the feed-in limit over the course of the day. In addition to considering PV power and load demand forecasts, further improvements of the grid integration can potentially be realised by taking present and past measured grid voltage data of the site into account. This allows limiting the feed-in appropriate to the local requirements of the distribution system.

6. Conclusion

In summary, this analysis shows that the self-consumption rate and the degree of self-sufficiency strongly depend on the PV system and battery size. Nevertheless, only a small impact of the PV generator orientation on the degree of self-sufficiency for a residential PV battery system was determined. This may lead to the conclusion that the orientation of the PV generator will be of smaller relevance in the future than in the past, where the absolute yield was the crucial factor. Based on the simulation results, an economic assessment of PV battery systems was carried out, which reveals that the cost-optimal system configurations are strongly affected by the cost situations. It was identified that the optimal PV system size will shrink to small-scale systems with higher self-consumption rates, as the incomes from the feed-in payments will play a minor role in future. In the considered long-term scenario the conjunction of PV systems with batteries will be not only profitable but also the most economical solution.

Another focus of this paper was the grid integration of PV battery systems. If the operation strategy of maximising self-consumption is implemented into PV battery systems, neither the maximum feed-in power nor the maximum ramp rates of the grid feed-in will be reduced. By limiting the grid injection, the grid load is reduced in terms of peaks and ramps of the feed-in power. The results reveal that a compromise between the feed-in limit, the installed battery size and the curtailment losses is required. It can be reasonable to permit small amounts of curtailed energy in order to achieve the objective of setting the maximum feed-in power as low as possible. The highest reduction of the feed-in power is realised by operation modes taking PV power and load forecasts into account. This emphasizes the importance of implementing forecast-based operation strategies into PV battery systems. Therefore, the conjunction of PV systems with batteries is of decisive importance, not only to increase the hosting capacity of the electricity grid for PV systems, but also to tap the whole PV potential.

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